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GROUND TESTING OF THE WIDE FIELD/PLANETARY CAMERA - II OR "BRINGING HUBBLE BACK INTO FOCUS"

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Abstract

The Wide Field/Planetary Camera - II (WF/PC-II) is a scientific instrument that was installed on the Hubble Space Telescope (HST) in December of 1993. The camera replaced WF/PC-I (also built by JPL) and was designed to correct for the spherical aberration that is present on the Primary Mirror of HST. The unique application and design of the science instrument required that special attention be paid to both optical alignment and thermal stability. Since the camera is not a fully redundant instrument, it was critical that rigorous ground testing be performed. The current climate at NASA also resulted in a high visibility, "cannot fail" mission which needed to be delivered on schedule and within budget. In this paper, we detail the Integration and Test phases of the WF/PC-II Project which led to the delivery of the science instrument to Goddard Space Flight Center both ahead of schedule and under budget. Emphasis is placed on the system testing of the camera with particular attention paid to the Environmental testing phase. The discussion will include but not be limited to system ambient testing, vibration testing, acoustic testing, and thermal vacuum testing. Special attention is also placed on the issue of contamination since the primary advantage of HST over ground-based telescopes is ultraviolet (UV) performance which is extremely sensitive to molecular contamination.

1. Introduction

The WF/PC-II, shown in figure a, is a 610 pound, Charge Coupled Device (CCD) camera with three f/12.9 channels and one f/30 channel. The WF/PC-II is the instrument of choice by astronomers for more than half of HST observations. The instrument has a field of view equivalent to a square of 150 arcseconds on a side. Prior to the discovery of the spherical aberration on HST, it was intended that the WF/PC-II merely be a "clone" of WF/PC-I with upgraded CCD detectors. The many differences between the two cameras exist not only due to the correction for the aberration, but also for other reasons that will be addressed.

2. Optics

The WF/PC Optical path is shown in figure b. The incoming light from the Optical Telescope Assembly (OTA) of HST is reflected off the pickoff mirror and travels into the WF/PC-II. It travels through the

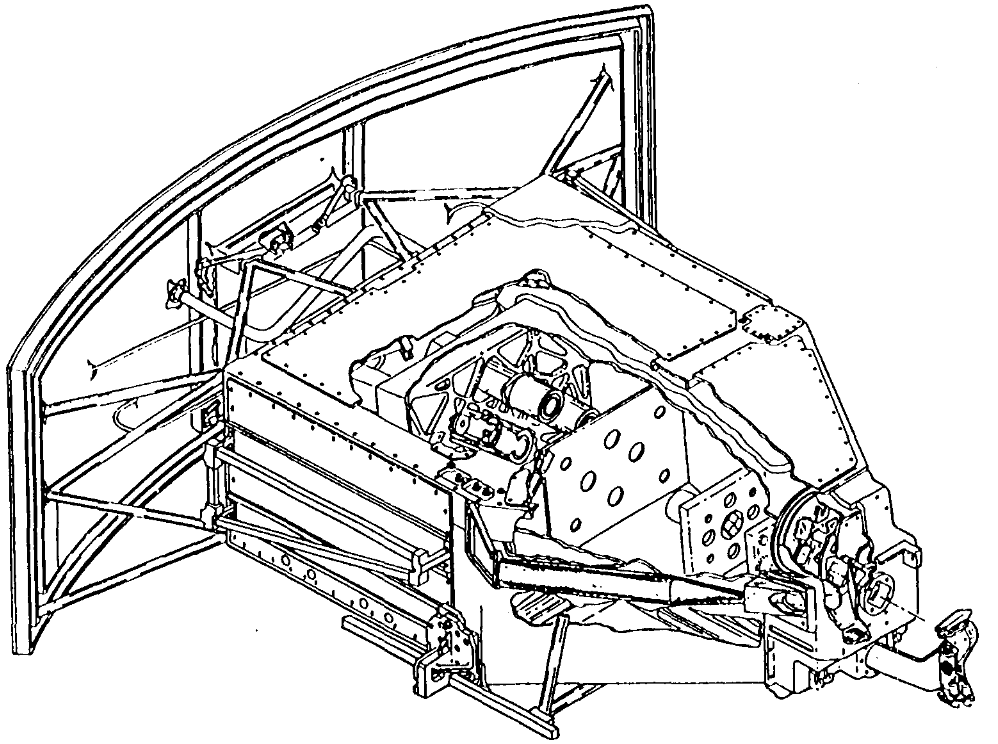

fig. a. The Wide Field Planetary Camera -II

butter and optical filter assembly before striking the pyramid, which splits the beam into four parts and reflects the light to the respective channels. The light then strikes the fold mirrors which steer the respective beams toward the relay optics. The relay optics contain the secondary mirrors upon which the correction for the spherical aberration occurs. Finally, the detectors are located at the end of each relay optics barrel.

In WF/PC-I, the pyramid could be rotated in order to switch from the four Wide Field (WF) channels to the four Planetary (PC) channels. On orbit, the WF/PC-I pyramid mechanism had demonstrated a drift in the range of 1 arcminute per year. This drift would have required frequent compensation throughout the life of WF/PC-II. It was decided early in the program that rather than flying an optical configuration identical to that of WF/PC-I, the design could be made more robust and stable by reducing from 4 Planetary channels and 4 Wide Field channels to 3 Wide Field and 1 Planetary. The Scientists felt that this was a good trade off since it got rid of the inherently unstable pyramid mechanism, but only slightly reduced the nominal field of view. additionally freed up the resources to fund the Articulating Fold Mirror (AFM) development.

The correction for the spherical aberration involved putting an aspheric figure on all four of the relay optics secondary mirrors (see figure b). Additionally, it was necessary to slightly change the power on the PC fold mirror. The change from eight channels to four that is described above involved the movement of the remaining PC channel into the removed WF channel slot. This in turn caused a misalignment of the spider of the relay optic with the HST spider. Rotation of the relay optic solved this problem.

Correction of the spherical aberration on a relay secondary the size of nickel created its own set of technical problems, namely, pupil alignment. In order for the correction of the spherical aberration to work properly, it was critical that the optics with the corrective surface be precisely aligned with the incoming optical beam. This constraint is much tighter than on WF/PC-I. This concern over alignment led to the

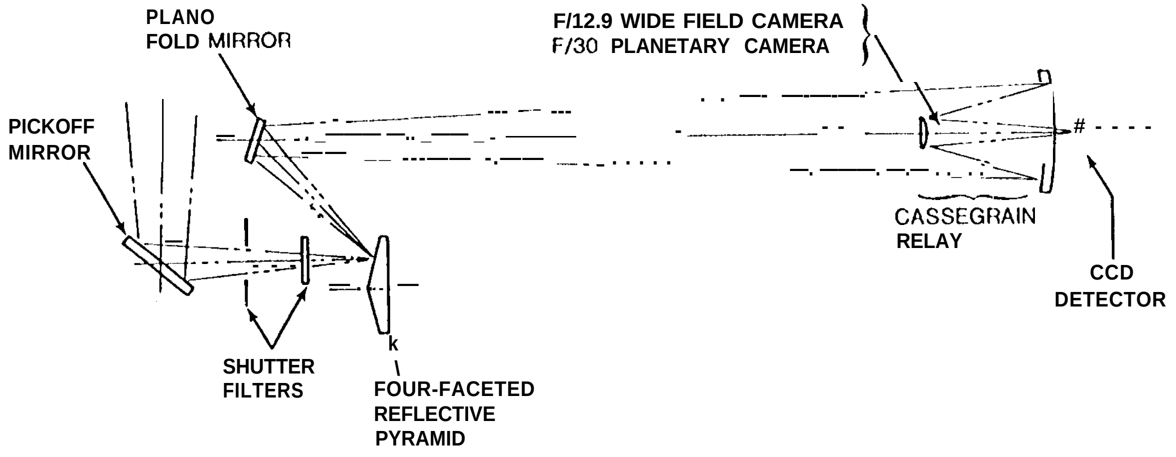

fig. b. WF/PC-II Optical Schematic

mplementation of two new mechanisms. The first new mechanism is the Articulating Fold Mirror (AFM). We incorporated AFM's into the PC fold mirror as well as two of the three WF fold mirrors. These AFM's are electrostrictive ceramic actuators within the Fold Mirror structure that provide tip/tilt adjustments up to 206 arcseconds in each axis in steps of 1 arcsecond (see figure c). The second new mechanism is the pickoff mirror mechanism. This mechanism provides the capability to tip/tilt the pickoff mirror in increments of 12 arcseconds for a total range of 900 arcseconds. The logic behind the two mechanisms was that the pickoff mirror mechanism can be used to align the pickoff mirror ideally for the fixed fold mirror channel, and then the AFM's cart be used to optimize the other three channels.

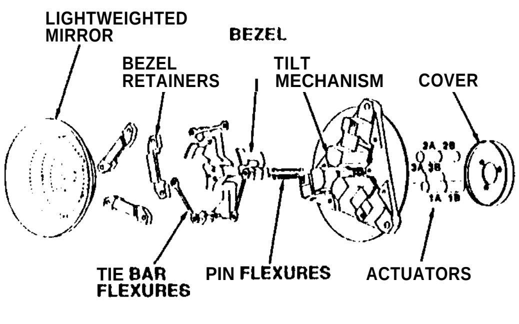

fig. c. Articulating Fold Mirror

ı order to verify that we would be able to maintain our alignment through the launch environment, we performed extensive optical tolerancing and developed a detailed error budget. A part of this budget, of course, included the vibration sensitivity of each optical component. Consequently, early in the program, we vibrated all of the optical components at the subsystem level bolted to a simulated optical bench bulkhead. The results from this testing aided us in understanding stability characteristics of the various components, which could be fed into the error budget.

The first generation camera (WF/PC-I) had CCD's with an instability known as Quantum Efficiency Hysteresis (QEH). In order to correct for QEH, it was necessary to periodically flood the CCD's with UV light from the sun. In order to accomplish this, we built the UV light channel which consisted of a mirror on the radiator which when pointed at the sun would bounce light into a light pipe where it was carried to the CCD's through a combination of optics. The new Loral CCD's used on WF/PC-II do not have the QEH problem. It was therefore decided to convert the light pipe into a calibration system that would allow for on-board calibration during occultation periods. Previously, "streak flats" or flat field calibration images of the ocean or cloud cover were used to provide calibration data. The on board calibration system greatly improved the efficiency of HST and contains both visible and UV sources.

One of the recurring themes within the WF/PC testing program is that of independent verification. Given the flaw on the primary mirror of HST, this attention to independent verification was particularly strong in the area of optics. The **primary** tool for verifying the correct implementation of the optical correction is known as the stimulus. The stimulus was designed to replicate exactly the aberrated optical beam as it exists on HST. The final and most comprehensive check of the ability of WF/PC-II to perform optically would be in the thermal vacuum test. Due to the inability to operate the detectors in an ambient environment, we would have to wait until then. In the mean time, optical alignment and verification was performed by several alternate and independent means which are described below.

We designed and built a mini-stimulus which, as the name implies, was a small version of the stimulus. The mini-stimulus allowed us to align and check out the optical train prior to system integration.

Secondly, we removed the detectors from the relay optics assemblies and installed retro-reflectors in their places. This allowed us to use the stimulus and perform double pass interferometry on each of the optical channels. This proved to be the most precise alignment and verification tool other than the thermal vacuum test.

Additionally, an independent team from Goddard came to JPL with an Aberrated Beam Analyzer (ABA) that was used to capture, analyze, and document the beam created by the stimulus, The purpose of this test was to insure that the tool we were using as our standard was, in fact, accurate.

Finally, several null lenses of different design were fabricated and used to verify the optical properties of both the stimulus and mini-stimulus.

3. Detectors

The WF/PC-II CCD's are Loral 800 X 800 front-side illuminated, lumogen coated detectors. They are far superior to the WF/PC-I CCD's in that they" have no Quantum Efficiency Hysteresis (QEH), deferred charge, or residual image problems. Additionally, they have about 7 electrons of read noise and are cosmetically excellent. It is important to point out that these detectors are cooled by Thermoelectric coolers (TEC's) and operate at -55 degrees C or below. Therefore, the CCD's cannot be operated in an ambient environment without causing permanent damage to the hot junction of the TEC as well as contaminating the detector window. As a result, a system thermal vacuum test is required in order to fully verify instrument function. The risk is that the system thermal vacuum test is traditionally run at the end of a project with no time to recover in case of difficulties. The solution to this will be discussed.

4. Mechanisms and Structures

The WF/PC-II Optical bench and radiator are flight spares from WF/PC-I. The bench is graphite epoxy with invar bulkheads for the mounting of the various optics (see figure d). The housing for WF/PC-II is basically a rebuild of the first one with some minor modifications. The change for

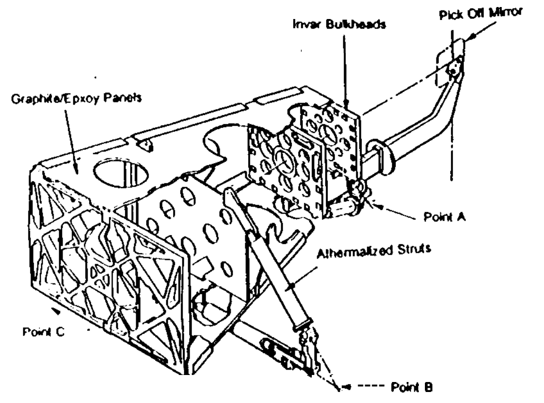

fig. d. WF/PC-II Optical Bench

WF/PC-II that had the most impact is in the area of materials. Due to the "emphasis on cleanliness in both particulate and molecular arenas, all materials had to be approved by the contamination representative. In the case of lubricants and adhesives, only very small amounts could be used and they had to be from the approved list. Additionally, all materials added to the instrument were logged, including cable ties, lubricants, adhesives and string tie.

In depth metrology was performed at JPL in order to verify the tight tolerance fit of the instrument in the HST. This was also verified when the instrument was installed into the HST Simulator at Goddard Space Flight Center (GSFC). Additionally, it was required that the WF/PC-II fit precisely into the Scientific Instrument Protective Enclosure (SIPE), which is the container that carried it aboard the shuttle.

The addition of the previously mentioned AFM's required us to add on the analog and digital electronics boxes to the outside of the housing. These were very close tolerance items and were scrutinized during the metrology sessions. Finally, it became apparent during the astronaut training sessions that some supplementary handholds would be required on the instrument to facilitate handling during the camera changeout. The handholds were designed by JPL, fabricated and delivered as Government Furnished Equipment (GFE) from Goddard, and installed at JPL.

5. Thermal

The WF/PC-II thermal design was very similar to that of WF/PC-I. One new constraint was the tightened optical bench stability requirement of 0.07 degrees C per 3000 seconds. This was dictated by the temperature sensitivity of the Lead-Magnesium-Niobate wafer stacks of the AFM's. An on-board applications processor controlling the replacement heaters in conjunction with some tailored thermal blanketing allowed the meeting of this requirement, The thermal performance of the camera was verified during the thermal vacuum test.

6. Electronics

The WF/PC-II electronics are a rebuild of the WF/PC-I electronics with some modifications to support the following:

- calibration system
- pickoff mirror mechanism
- AFM's
- 8 detectors to 4 detectors
- correction of WF/PC-I idiosyncrasies

There was a lot of emphasis placed on the ambient testing of the electronics and, in particular on getting as many burn-in hours as possible. Early in the project, we established a goal of 1500 hours of trouble free operations prior to launch. The actual verification of the electronics took place during the thermal vacuum test where realistic on-orbit conditions could be simulated. This includes such things as operating CCD's at all temperature set points in order to verify noise contribution of electronics, performing cold starts, as well as voltage and temperature margin tests,

7. Contamination

The Ultraviolet imaging benefit of being outside the atmosphere could be compromised by even a small number of monolayer of molecular contamination. To insure cleanliness, the contamination team developed a contamination budget much like the optics error budget, The contributions used in the budget were based on a contamination analysis program model which took into account all contamination sources and paths as well as venting. There have been numerous publications on the technical details of this effort, Each component of the instrument had a specific allocation that it was required to meet, This includes all lubricants and adhesives, tapes, and cable ties, Materials were carefully screened before selection and each component of the camera was painstakingly baked out in a chamber. In addition to this, additional steps were taken to install zeolite molecular adsorber blocks in strategic locations and to change the venting path of the camera. It was also required that WF/PC-II conform to an extremely high level of particulate cleanliness.

Once the integration of the camera had begun, continuous dry nitrogen purge was maintained throughout the project duration until launch. In addition to the purge, we monitored the particulate contamination throughout the project by employing wipe samples, non-volatile residue (NVR) plates, tape lifts, as well as an airborne particulate monitoring system. Concern over hydrocarbon contamination led us to install an activated charcoal filtration system in the clean room. Thermally controlled quartz crystal microbalance instruments were used to monitor molecular contamination during the bakeout process as well as in the thermal vacuum test. Stainless steel enclaves were fabricated for many of the bakeout chambers which did not otherwise clean up well enough to meet the required levels.

8. Integration

The integration of the instrument was very schedule limited and, therefore, a multi-shift enterprise, All integration activities took place within the JPL Spacecraft Assembly Facility **(SAF),** which is a 70' by 70' by 70' class 1000 clean room. The integration of the instrument consisted of three elements: electrical, mechanical, and optical. The installation of the optical elements onto the optical bench and subsequent alignment took place on one side of the room, while the electrical and mechanical integration was going on in parallel on the other side of the room involving the housing and electronics bays. The optical bench could be integrated in a stand-alone fashion and, following completion of the electrical and mechanical work to the instrument housing, was inserted into the housing (see figure e). The electronics bays of the instrument provide stiffness to and comprise a major part of the structure of the instrument. Therefore, electrical and mechanical integration needed to occur in the same place. While the optics work was taking place on a single 6 day/week 12 hour **shift,** the mechanical and electrical work were occupying first and second shift respectively.

To be added:
JPL Photo 20380 CC

fig. e. Insertion of Optical Bench into Housing

The previously mentioned goal of 1500 hours of trouble free operation on the instrument prior to launch was accomplished by careful planning and usage of resources. The members of the integration and test team were always intended to transition into the core team responsible for the operations of the instrument in the post launch environment. Training for both the thermal vacuum test and post launch operations were performed on the flight instrument, allowing additional operating hours to get logged.

9. System Testing

Following the successful integration of the WF/PC-II, the following system testing was performed:

JPL

- system functional testing
- EMI/EMC testing
- alignment of the optical bench to the housing verification
- independent optical verification
- pre-dynamics optical alignment testing
- dynamic testing (vibration and acoustic)
- post-dynamics optical alignment testing
- thermal vacuum and calibration
- mass and center of gravity,

GSFC

- mechanical interface verification (both HST and SIPE)
- electrical interface verification
- commanding validation
- stray light test
- confocality test

KSC

- repeat confocality testing
- final functional testing
- configure instrument to launch mode

We established a baseline set of functional tests that were carried from the integration phases of the program all the way to the on-orbit functional testing. These tests consisted of an Aliveness Test, a Short Form Functional Test, and a Long Form Functional Test. Following any transportation of the instrument, functionality would be verified by running this group of procedures. This also allowed us to carry a baseline of instrument performance throughout the project.

The EMI/EMC testing of WF/PC-II was essentially a repeat of the testing performed on WF/PC-I. The only changes of interest were the new mechanisms and associated electronics.

As discussed earlier, we were quite concerned about waiting until the system thermal vacuum test to verify the instrument optical alignment as well as detector performance, The running of a thermal vacuum test comes at considerable logistical as well as budgetary expense, It was at this point that we came up with the idea of performing a pre and post dynamics optical alignment test. The concept was simple. We could perform a one-day nitrogen environment test in the thermal vacuum chamber without pumping down and still verify the optical alignment and gross detector performance at a fraction of the cost of running a full thermal vacuum test. The running of this one-day test, just prior to and following dynamics testing allowed us to verify that no optical components had moved more than the amounts specified in the error budget. The detectors were cooled down to 5 degrees C by thermally driving the radiator with a thermal shroud. The detector temperature of 5 degrees C was selected based on the minimum acceptable detector dark current which rises with the temperature. While we still had about one half full well of dark current, we gained additional confidence in the operation of the detectors,

The dynamics testing of the WF/PC-II consisted of a single axis Force limited random vibration in the launch axis as well as acoustic testing. The random vibration test level was 0.02 g^2/Hz, 2.9 g rms. The acoustic test was run at 147 dB. WF/PC-I was required to survive a shuttle launch installed inside HST while WF/PC-II was installed in the SIPE in the shuttle bay. We were assured by the HST Project at GSFC that the loads would be less than or equal to those experienced by WF/PC-I. This was confirmed by a subsequent SIPE vibration test.

After careful analysis, it was determined that single axis testing would suffice due to considerable cross-coupling in the other two axes. Additionally, a low level sine sweep was performed both prior to and following the random vibration in order to assure no changes had occurred. While force limited testing has been used at the component and subsystem level, but this was the first use of force limited testing on a JPL instrument. There have been several publications on the implementation and results using force limited testing on **WF/PC-II.**

The thermal vacuum test was the single most important milestone in the entire development of the camera. This is where the thermal design is verified, alignment is checked, electronics and mechanisms are put through their paces, and the Science Team get their calibration baseline that will be used for years to come to analyze on-orbit data.

The test was **timelined** to last 32 days as shown in figure f. The engineering requirements for the test were defined by the System Engineer with the Science Requirements coming from the Science Team. The first several days were spent in a soak at 35 degrees C to drive much of the water out of the graphite epoxy optical bench and in order to create the ultra clean environment required when operating the detectors at -55 degrees C and below. This thermal soak also satisfied the Flight Acceptance Hot requirements for the instrument. This bakeout period was followed by the hot nominal orbit, nominal orbit, cold nominal orbit, and Flight Acceptance Cold periods of the test, Meticulous planning was undertaken with the Science Team in order to get all of the engineering tasks as well as a myriad of calibration tasks accomplished. The calibration of the filter set, UV performance, detector characterization, as well as long and short term stability tests comprise just a fraction of the calibration plan.

Three **shifts** containing ten positions each were used to support the test. These positions included a test chief, console operator, data logger, Science Team members, chamber support personnel, as well as management. We invited some of the **GSFC** and contractor support personnel who would soon be tasked with operating the **WF/PC** on orbit to participate in the test. Rather than having them merely observe as had been done in the past, these personnel were actually assigned **shift** positions and supported the test. In retrospect, this was an insightful decision which has greatly benefited the team operating the camera today,

During the test, a test status meeting was held each **afternoon** at which all problems were addressed. The key to the success of the test, which concluded successfully as planned, was flexibility. The instrument was run continuously for 32 days with no idle

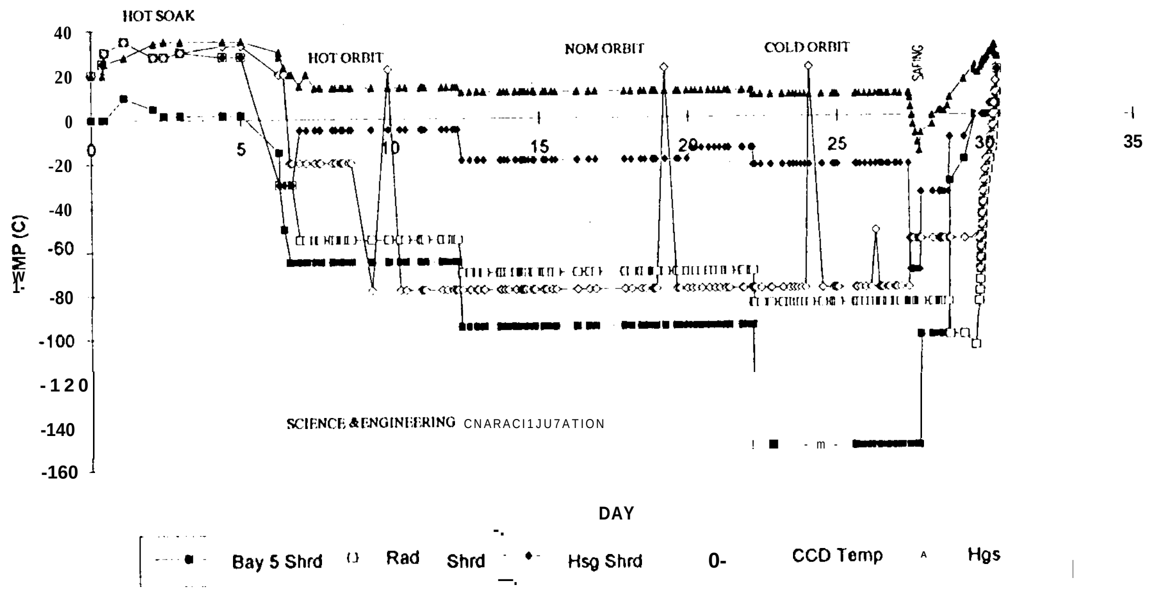

fig. f. Thermal Vacuum Test Timeline

periods. The procedure replan and development, caused by various technical challenges, was often completed only minutes before it was run. It is likely the first time in history that the Principal Investigator and the Science Team could not come up with any additional tests to run.

Following the shipment of the instrument to GSFC, the mechanical interface verifications were performed. The first half of this task was the installation of the camera into a high fidelity mechanical simulator of HST that GSFC had built using the as built HST data. The second half of this task was the installation of the camera into the SIPE which would eventually carry the camera to orbit.

Additional testing that was performed at GSFC was in the areas of electrical compatibility, commanding, and optics. In addition to the mechanical HST simulator, GSFC has also built a full electrical simulator of HST. This enabled us to mate the WF/PC with flight connectors to the HST simulator and run our full set of functional tests. Following this validation, we tested all of the flight and ground software that had been written to operate the WF/PC on orbit, including changes to the commanding and telemetry database. This was critical due to the changes that had occurred between WF/PC-I and -II. Finally, the optical testing at GSFC consisted of stray light testing and confocality testing. These two tests were intended to be "sanity checks" looking for gross errors that had somehow slipped through. The stray light test was intended to show that there would be no adverse effects to HST imaging due to stray light or reflections. This test went off fairly well, although many questioned its value. The confocality test was a disaster. The purpose of the test was to verify that the WF/PC and the Corrective Optics Space Telescope Axial Replacement (COSTAR) were confocal with respect to the OTA. The test was not well planned and, due to the incredible pressure and visibility of the test, many forgot that it was intended as a sanity check, In the end, errors were made in the calibration of test equipment and therefore, in the analysis of test data. Consequently, a different test was designed by JPL engineers to confirm the WF/PC-II focal position and was run at Kennedy Space Center (KSC).

At KSC, final functional testing of the WF/PC was performed. Once again this data was compared to the baseline data from the previous runs of the functional tests. Additionally, the flight pickoff mirror, which had been removed to protect it from any contamination, was reinstalled and aligned. The redesigned confocality test was run, and the results showed that all was as it should be. The final activity was to perform all red tag items and command the instrument into the Launch configuration.

10. Management

The WF/PC-II Project was managed in a somewhat new way for JPL. The Project Manager selected Task Managers for the following disciplines:

- structures/mechanisms
- optics
- science
- contamination
- product assurance
- integration and test
- electronics
- system engineering

In the past at JPL, a flight project would have cognizant engineers in addition to division representatives assigned to it, who would attempt to provide solutions to any problems which arose in the project. Divisions, not people, had responsibility for delivery of a particular piece of hardware or service. On WF/PC-II, that responsibility fell on a person who took ownership for the particular deliverables. While this sounds like a subtle difference, the impact was quite profound. All Task Managers, as well as the Project Manager, met together at 8:00 a.m. every morning for two years. There was no lack of communication among team members, and excuses of misinformation were not tolerated.

During the peak periods of Integration and Test of the instrument, there were over 100 people working on the Project. Managing a team of this size in addition to planning and running a 32-day thermal vacuum test presented a challenge. One key to success was the ability to maintain great flexibility in the scheduling and performance of tasks. There wasafull-time person on the project who maintained the Project Management System (PMS) which allowed for real time problem solving and replanning. Specifically, the PMS contained an integrated network to track the entire project. This network consisted of over 1000 nodes. It was quite easy to determine status against plan at any given time. If anyone started falling behind the plan by more than 3 or 4 days, immediate contingency planning was begun with descopes clearly identified in order to enable the project to return to plan.

While the Integration and Test Manager maintained overall responsibility for the test program, individuals were assigned as task leaders for key tests such as EMI/EMC, dynamics testing, and thermal vacuum. These individuals were selected from the existing Integration and Test team.

Finally, the project held monthly management meetings which served to inform Goddard Space Flight Center (the customer), as well as senior JPL management as to the technical, schedule, and financial status of the project. During these meetings, each of the previously described task managers would have to stand up and provide a status for and defend their respective areas. This again emphasizes the importance of getting individuals to take ownership of particular subsystems.

Conclusion

The Integration and Testing of the WF/PC-II instrument is an example of what can happen when a motivated group of individuals get together and form a team. When technical and programmatic problems arose, members of the team were called upon to exercise good engineering judgment and come up with novel solutions. With the possible exception of the AFM's, there are no remarkable new technologies revealed here, but it is clear that a well thought out plan was implemented successfully, and there exists an opportunity to share in lessons learned.

Acknowledgment

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